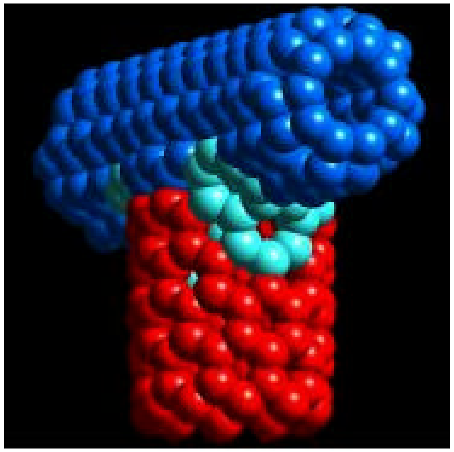
Nanotechnology: What is Ahead?

M. Meyyappan
NASA Ames Research Center
Moffett Field, CA 94035
meyya@orbit.arc.nasa.gov

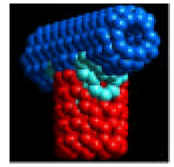


http://www.ipt.arc.nasa.gov

Plenary Talk

IEEE Aerospace Conference, Big Sky, Montana, March 19, 2000

Outline



- What is Nanotechnology?
  - Background
- National Nanotechnology Initiative
- Nanotechnology
  - Materials and Manufacturing
  - Health and Medicine
  - Energy and Environment
  - National Security
  - Nanoelectronics and Computing
- Carbon Nanotubes: A closer look
- Summary

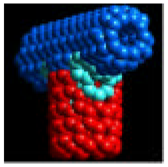
Acknowledgement:
Information on National Nanotechnology Initiative is from the Interagency Working Group on Nanotechnology (IWGN) Reports

What is Nanotechnology?

Nanotechnology is the creation of functional materials, devices and systems through control of matter on the nanometer length scale and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale

"If I were asked for an area of science and engineering that will most likely produce the breakthroughs of tomorrow, I would point to nanoscale science and engineering."

-Neal Lane
Assistant to the President for Science
And Technology



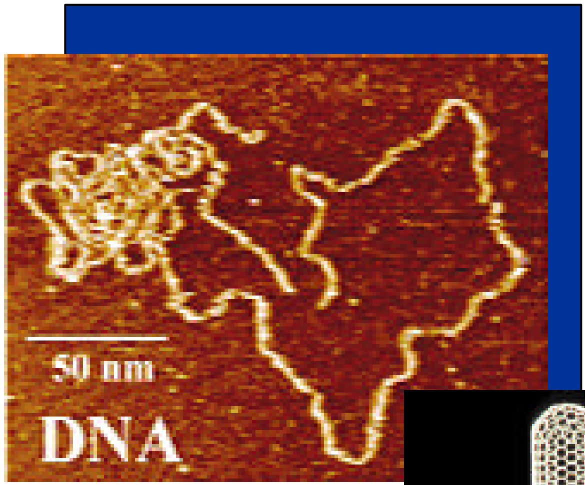
Examples of Nanostructures

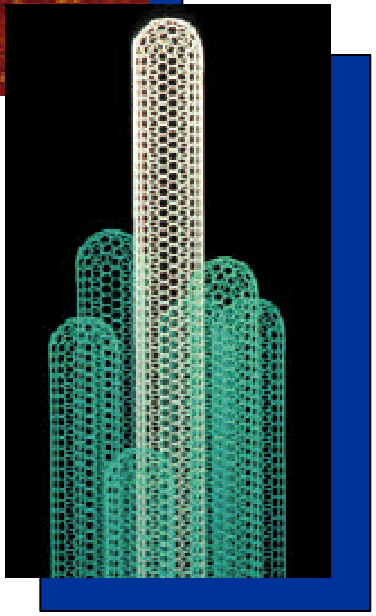
- New behavior at nanoscale is not necessarily predictable from what we know at macroscales.

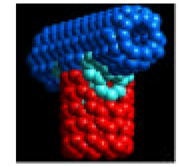
- Not just size reduction but phenomena intrinsic to nanoscale
  - Size confinement
  - Dominance of interfacial phenomena
  - Quantum mechanics

- Examples
  - Carbon Nanotubes
  - Thin Films
  - Proteins, DNA
  - Single electron transistors

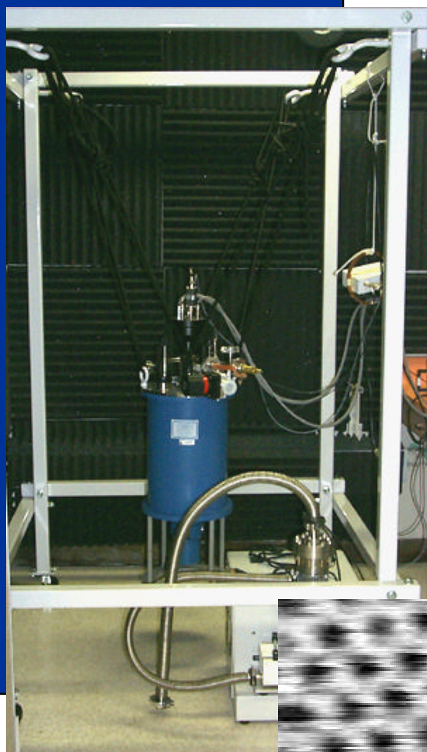
AFM Image of DNA







Nano Revolution



STM

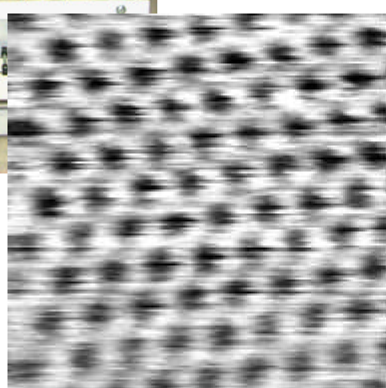


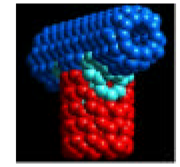
Image of Highly Oriented
Pyrolitic Graphite

- 1959 Feynman Lecture *"There is Plenty of Room at the Bottom"* provided the vision of exciting new discoveries if one could fabricate materials/devices at the atomic/molecular scale.

- Emergence of instruments in the 1980s; STM, AFM providing the "eyes", "fingers" for nanoscale manipulation, measurement…

- Recently, there has been an explosion of research on the nanoscale behavior
  - Nanostructures through sub-micron self assembly creating entities from "bottom-up" instead of "top-down"
  - Characterization and applications
  - Highly sophisticated computer simulations to enhance understanding as well as create 'designer materials'

Impact of Nanotechnology



“The emerging fields of nanoscience and nanoengineering are leading to unprecedented understanding and control over the fundamental building blocks of all physical things. This is likely to change the way almost everything - from vaccines to computers to automobile tires to objects not yet imagined - is designed and made.” - from IWGN Report

Societal and Economic Benefits

- Materials and Manufacturing
- Nanoelectronics and Computing
- Medicine and Health
- Environment and Energy
- Transportation
- Aeronautics, Space exploration
- National Security

“As we enter the 21st century, nanotechnology will have a major impact on the health, wealth and security of the world’s people that will be at least as significant in this century as antibiotics, the integrated circuit, and man-made polymers.” - from IWGN Report

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National Nanotechnology Initiative

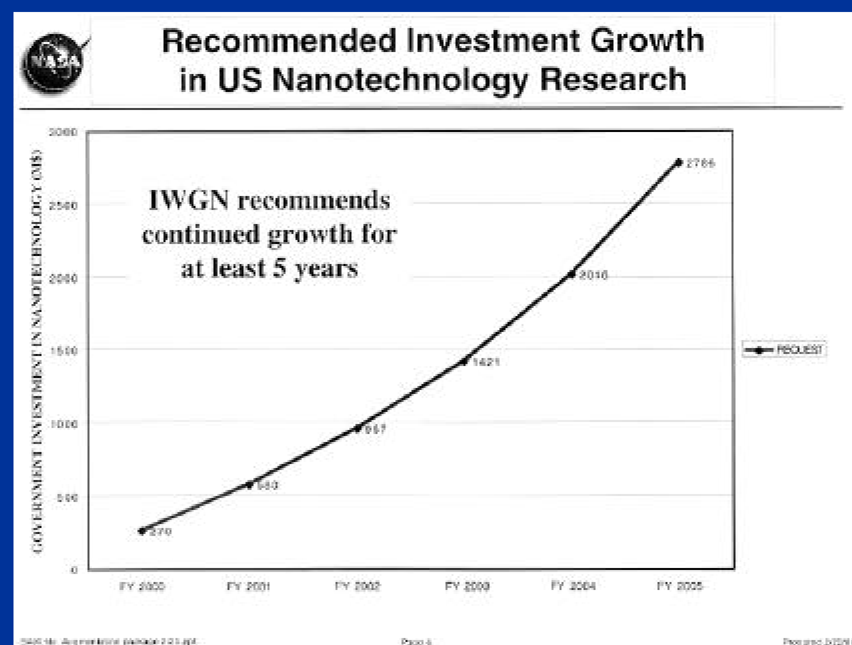
- For information, www.nano.gov
- Multiagency Initiative in nanotechnology starting in FY01 “National Nanotechnology Initiative (NNI) - Leading to the Next Industrial Revolution”
- NNI History
  - President’s National Science and Technology Council (NSTC) establishes an Interagency working group on Nanotechnology (IWGN) in Sept. 98
  - IWGN consists of representatives from various agencies
    - Mike Roco (NSF), chair; Tom Kalil (WH), vice-chair
  - NSF report on Nanotechnology activities abroad released in Jan. 99
  - IWGN brings experts together in Jan. 99 to create a broad vision for Nanotechnology
    - Nobel Laureates, Eminent Scientists from academia and industry, CTOs…
  - IWGN submits report to WH, congressional hearings (March-June, 1999)

Status of NNI

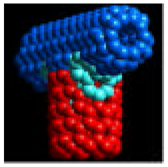
"My budget supports new National Nanotechnology Initiative, worth $500 million … the ability to manipulate matter at the atomic and molecular level. Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight -- shrinking all the information housed at the Library of Congress into a device the size of a sugar cube -- detecting cancerous tumors when they are only a few cells in size. Some of our research goals may take 20 or more years to achieve, but that is precisely why there is an important role for the federal government."

-- President William J. Clinton
January 21, 2000, California Institute of Technology

Agency Funding FY 01	
NSF	$ 217 M
DoD	$ 110 M
DOE	$ 94 M
NASA	$ 20 M
DOC	$ 18 M
NIH	$ 36 M
Total	$ 495 M



Nanotechnology Research Abroad



- The U.S. does not dominate nanotechnology research. Nearly twice as much ongoing research overseas as in the U.S. In 1997 Govt. expenditures on Nanotechnology Research: U.S.: $118 M, Japan: $120 M, Europe: $122 M, Others: $65 M.

- Many foreign leaders, companies, scientists believe that nanotechnology will be the leading technology of the 21st century. The fact that there is still a chance to get on the ground floor explains pervasive R & D worldwide. Strong nanotechnology programs in Singapore, Australia, Korea, Taiwan, China and Russia.

Leadership Position

Synthesis & Assembly	U.S.	Europe	Japan
Biological Approaches & Application	U.S./Eur	Japan	
Dispersions and Coatings	U.S./Eur	Japan	
High Surface Area Materials	U.S.	Europe	Japan
Nanodevices	Japan	Europe	U.S.
Level	1	2	3

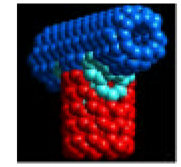
Highest

Source: WTEC Report

Grand Coalition

- **Academe** will play key role in development of nanoscience and technology
  - Promote interdisciplinary work involving multiple departments
  - Develop new educational paradigms
- **Private Sector** will invest only when products are within 3 years
  - Maintain in-house research, sponsor precompetitive research
  - Sponsor technology start-ups and spin-offs
- **Government Labs** can provide large scale facilities and infrastructure for nanotechnology research and can serve as technology incubators
- **Government Funding Agencies** provide funding through the NNI
- **Professional societies** should establish interdisciplinary forum for exchange of information; reach out to international community.

R & D Categories for Investment



AS Recommended by the IWGN Panel

- Nanostructure Properties
  - Biological, chemical, electronic, magnetic, optical, structural…
- Synthesis and Processing
  - Enable atomic and molecular control of material building blocks
  - Bioinspired, multifunctional, adaptive structures
  - Affordability at commercial levels
- Characterization and manipulation
  - New experimental tools to measure, control
  - New standards of measurement
- Modeling and simulation
- Device and System Concepts
  - Stimulate innovative applications to new technologies

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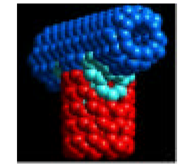
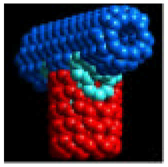
Some Fundamental Science Issues



1. What novel quantum properties will be enabled by nanostructures (at room temp.)?
2. How different from bulk behavior?
3. What are the surface reconstructions and rearrangements of atoms in nanocrystals?
4. Can carbon nanotubes of specified length and helicity be synthesized as pure species? Heterojunctions in 1-D?
5. What new insights can we gain about polymer, biological…systems from the capability to examine single-molecule properties?
6. How can one use parallel self-assembly techniques to control relative arrangements of nanoscale components according to predesigned sequence?
7. Are there processes leading to economic preparation of nanostructures with control of size, shape… for applications?

Materials and Manufacturing

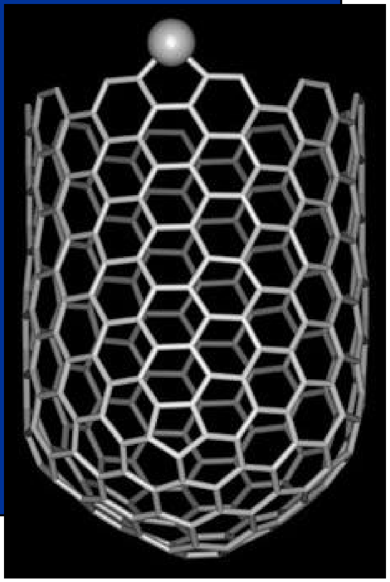


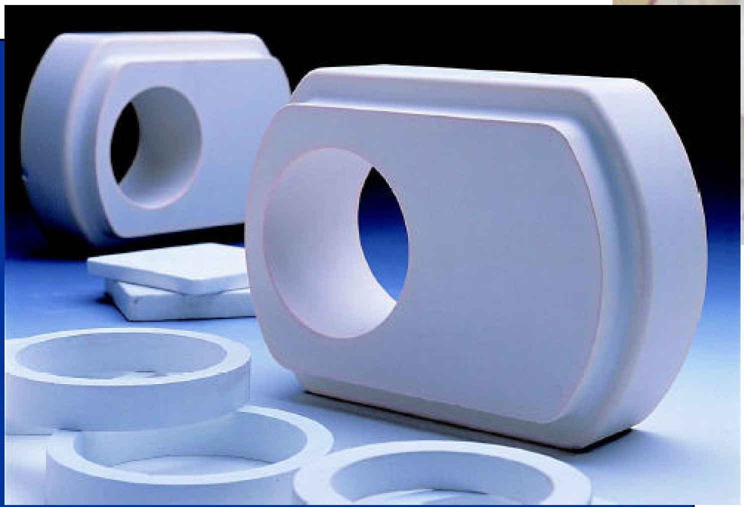
- Ability to synthesize nanoscale building blocks with control on size, composition etc. further assembling into larger structures with designed properties will revolutionize materials manufacturing
  - Lighter, stronger and programmable materials
  - Lower failure rates and reduced life-cycle costs
  - Bio-inspired materials
  - Multifunctional, adaptive materials
  - Self-healing materials
  - Manufacturing metals, ceramics, polymers, etc. at exact shapes without machining

- Challenges ahead
  - Synthesis, large scale processing
  - Multiscale models with predictive capability
  - Analytical instrumentation

Materials and Manufacturing
Some Recent Advances

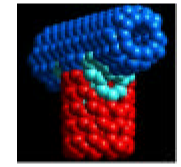
- Carbon Nanotubes
- Nanostructured Polymers
- Optical fiber performs through sol-gel processing of nanoparticles
- Nanoparticles in imaging systems
- Nanostructured coatings
- Ceramic Nanoparticles for netshapes





Source: IWGN Report

Health and Medicine



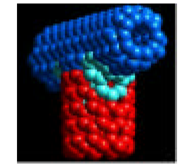
- Expanding ability to characterize genetic makeup will revolutionize the specificity of diagnostics and therapeutics
  - Nanodevices can make gene sequencing more efficient
- Effective and less expensive health care using remote and in-vivo devices
- New formulations and routes for drug delivery, optimal drug usage
- More durable, rejection-resistant artificial tissues and organs
- Sensors for early detection and prevention

Health and Medicine
Some Recent Advances

- DNA microchip arrays using advances for IC industry
- ‘Gene gun’ that uses nanoparticles to deliver genetic material to target cells
- Semiconductor nanocrystals as fluorescent biological labels

Source: IWGN Report

Energy and Environment



- Nanotechnology has the potential to impact energy efficiency, storage and production

- Monitoring and remediation of environmental problems; curbing emissions; development of environmental friendly processing technologies

- Some recent examples:
  - Crystalline materials as catalyst support, $300 b/year
  - Ordered mesoporous material by Mobil oil to remove ultrafine contaminants
  - Nano-particle reinforced polymers to replace metals in automobiles to reduce gasoline consumption

- Challenges ahead:
  - Nanorobots for environmental and nuclear waste management
  - Nanofilters to separate isotopes in nuclear processing
  - Nanopowders for decontamination

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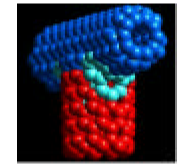
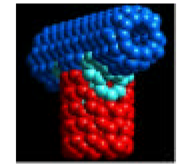
National Security



Some critical defense applications of nanotechnology include

- Virtual reality systems based on nanoelectronics for effective training
- Increased use of automation and robotics
- High performance, high strength, light weight military platforms while reducing failure rates and life cycle costs
- Chemical/biological/nuclear sensing
- Nano and micromechanical devices for control of nuclear defense systems

Nanoelectronics and Computing



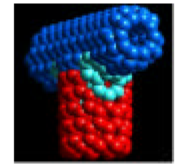
"There is at least as far to go (on a logarithmic scale) from the present as we have come from ENIAC. The end of CMOS scaling represents both opportunity and danger."

-Stan Williams, HP

- 4-8 CMOS generations left but cost of building fabs going up faster than sales. Physics has room for 10^9x current technology based on 1 Watt dissipation, 10^{18} ops/sec no clear ways to do it!
  - Molecular nanoelectronics
  - Quantum cellular automata
  - Chemically synthesized circuits

- Self assembly to reduce manufacturing costs, defect tolerant architectures are critical to future nanoelectronics

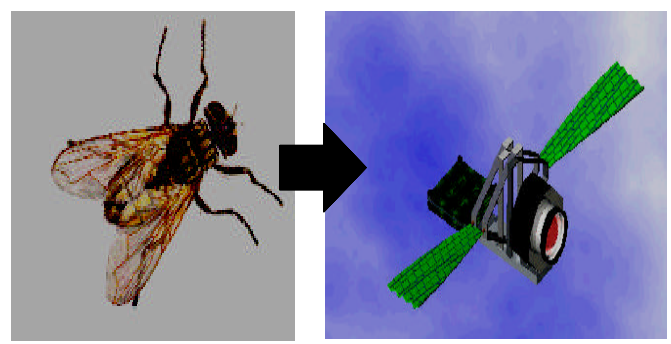
Nanoelectronics and Computing What is Up?



- Ubiquitous Computing as envisioned by Mark Weiser, Xerox PARC.

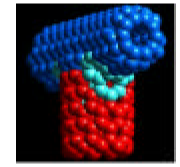
  Internet, bringing together elements of mainframe era and the PC era, represents *distributed computing*. The “UC era” will have a lot of computers sharing us; computers embedded in walls, chairs, clothing, light switches, cars…; characterized by the connection of things in the world with computation.

- *Biomimetics* is gaining momentum
  - One gram of DNA could possibly store all the data in the Library of Congress
  - The human brain contains about 10^{14} interconnects and operates at 10^{16} ops/sec using very low power and imprecise computing elements
  - Human immune system is a ‘self-repair’ system.



Biomimetics

Nanoelectronics and Computing
Some Recent Advances

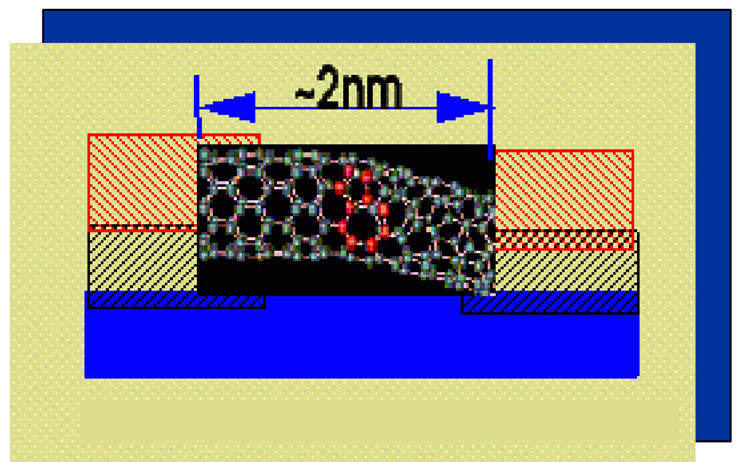


- Quantum Computing
  - Takes advantage of quantum mechanics instead of being limited by it
  - Digital bit stores info. in the form of ‘0’ and ‘1’; qubit may be in a superposition state of ‘0’ and ‘1’ representing both values *simultaneously* until a measurement is made
  - A sequence of N digital bits can represent *one* number between 0 and 2^N-1; N qubits can represent *all* 2^N numbers simultaneously

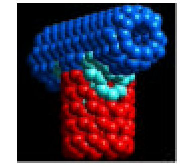
1938	1998
Technology engine: Vacuum tube	Technology engine: CMOS FET
Proposed improvement: Solid state switch	Proposed improvement: Quantum state switch
Fundamental research: Materials purity	Fundamental research: Materials size/shape

- Stan Williams

- Carbon nanotube transistor by IBM and Delft University
- Molecular electronics: Fabrication of logic gates from molecular switches using rotaxane molecules
- Defect tolerant architecture, TERAMAC computer by HP → architectural solution to the problem of defects in future molecular electronics



Why Nanotechnology at NASA?



- Advanced miniaturization, a key thrust area to enable new science and exploration missions
    - Ultrasmall sensors, power sources, communication, navigation, and propulsion systems with very low mass, volume and power consumption are needed
- Revolutions in electronics and computing will allow reconfigurable, autonomous, “thinking” spacecraft
- Nanotechnology presents a whole new spectrum of opportunities to build device components and systems for entirely new space architectures
    - Networks of ultrasmall probes on planetary surfaces
    - Micro-rovers that drive, hop, fly, and burrow
    - Collection of microspacecraft making a variety of measurements

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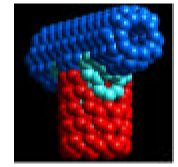
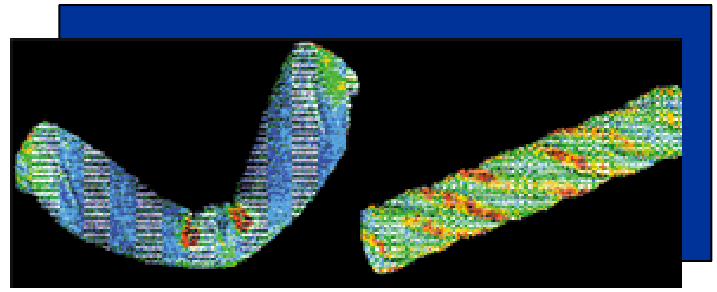
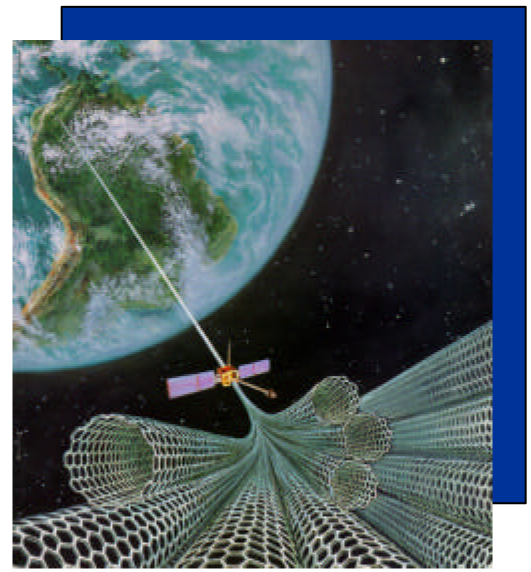
Carbon Nanotube

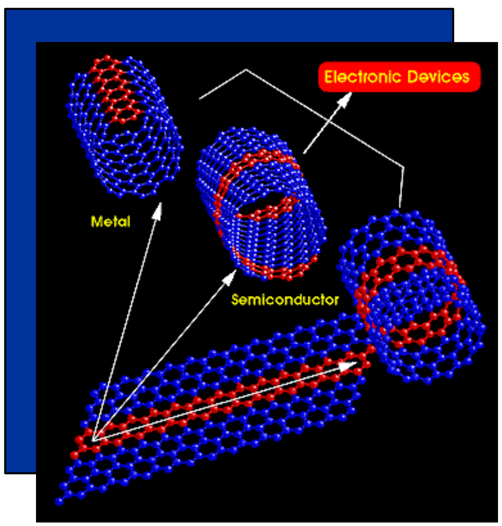


CNT is a tubular form of carbon with diameter as small as 1 nm.
Length: few nm to microns.



CNT is configurationally equivalent to a two dimensional graphene sheet rolled into a tube.



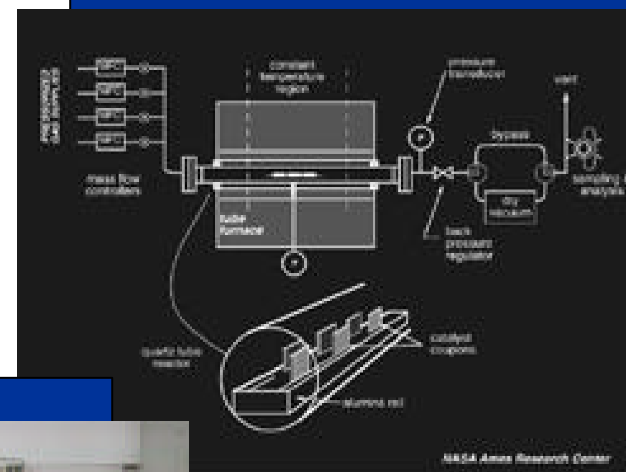


CNT exhibits extraordinary mechanical properties: Young’s modulus over 1 Tera Pascal, as stiff as diamond, and tensile strength ~ 200 GPa.

CNT can be metallic or semiconducting, depending on chirality.

CNT Synthesis

- CNT has been grown by laser ablation (pioneering at Rice) and carbon arc process (NEC, Japan) - early 90s.
  - SWNT, high purity, purification methods
- CVD is ideal for patterned growth (electronics, sensor applications)
  - Well known technique from microelectronics
  - Hydrocarbon feedstock
  - Growth needs catalyst (transition metal)
  - Multiwall tubes at 500-800° deg. C.
  - Numerous parameters influence CNT growth



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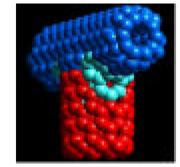
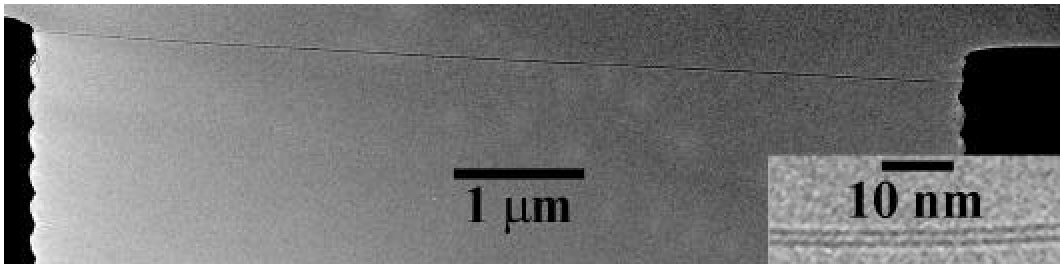
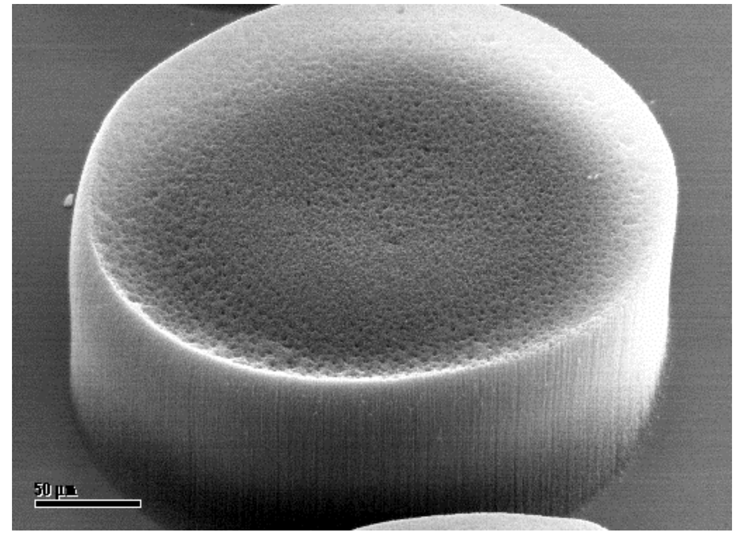
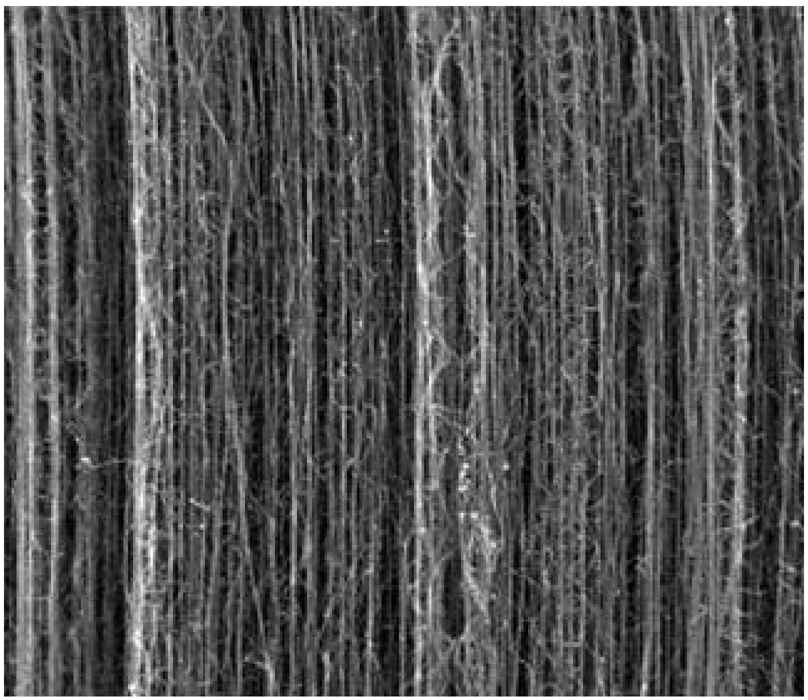
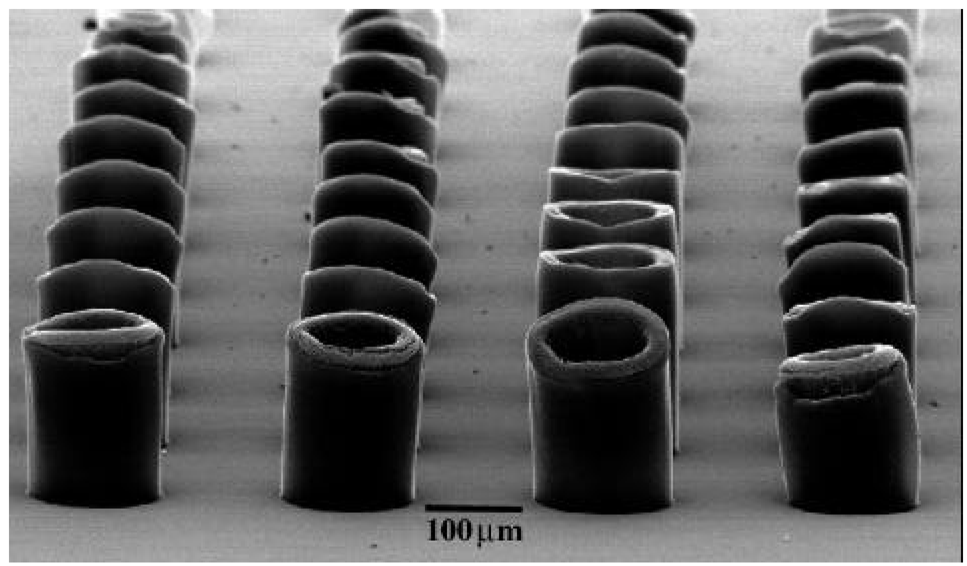
Carbon Nanotubes at Ames







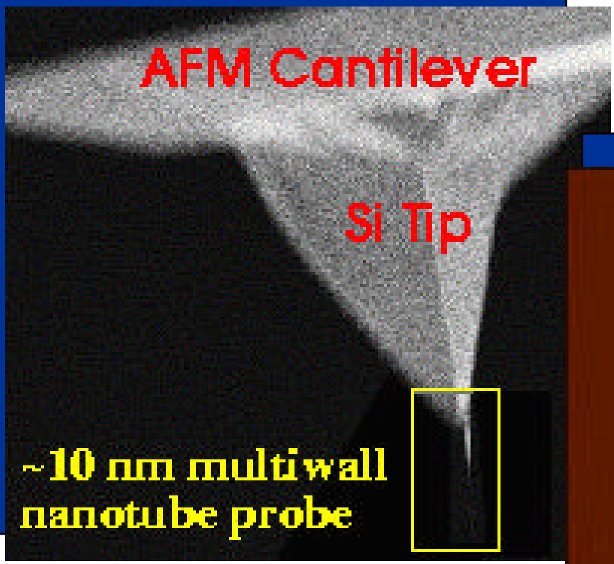




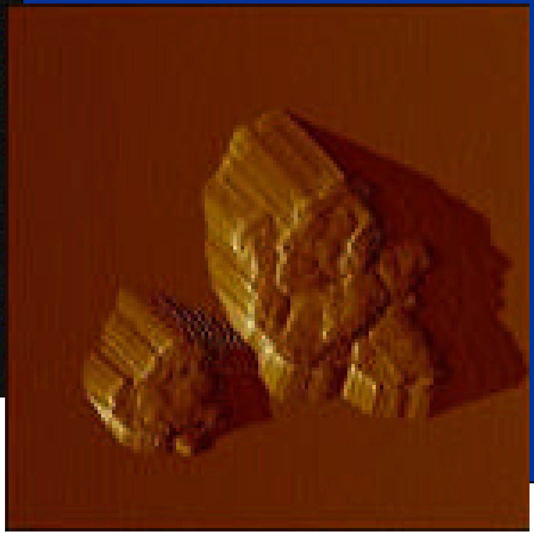
CNT in Microscopy

Atomic Force Microscopy is a powerful technique for imaging, nanomanipulation, as platform for sensor work, nanolithography...

Conventional silicon or tungsten tips wear out quickly. CNT tip is robust, offers amazing resolution.

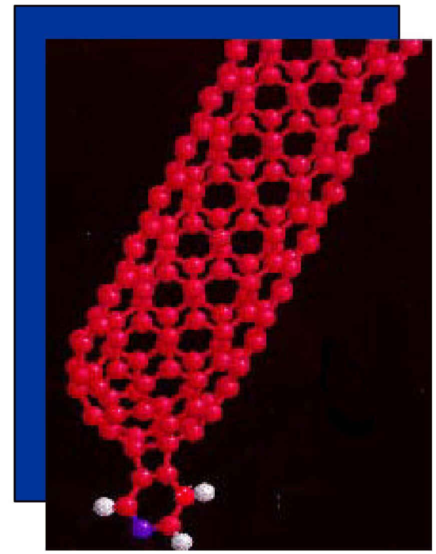


Simulated Mars dust



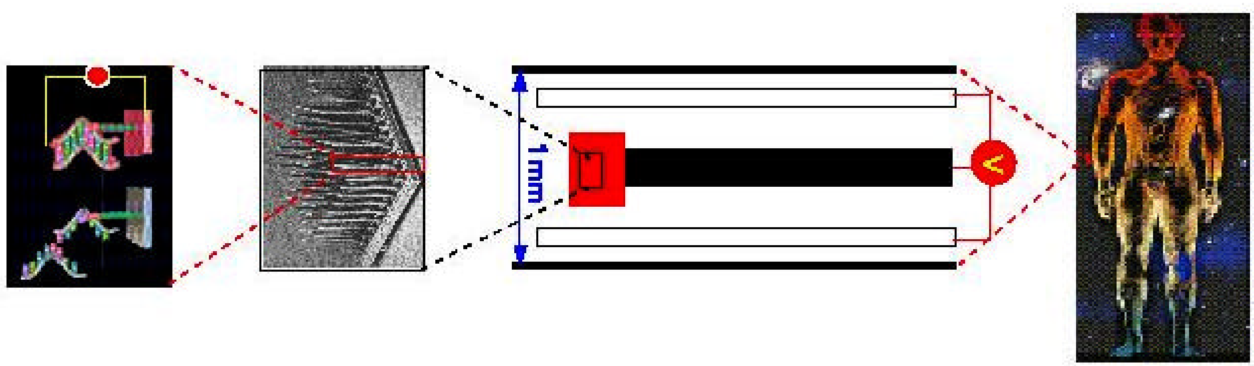
CNT Based Biosensors

- Our interest is to develop sensors for astrobiology to study origins of life. CNT, though inert, can be functionalized at the tip with a probe molecule. Current study uses AFM as an experimental platform.



- The technology is also being used in collaboration with NCI to develop sensors for cancer diagnostics
  - Identified probe molecule that will serve as signature of leukemia cells, to be attached to CNT
  - Current flow due to hybridization will be through CNT electrode to an IC chip.
  - Prototype biosensors catheter development

- High specificity
- Direct, fast response
- High sensitivity
- Single molecule and cell signal capture and detection



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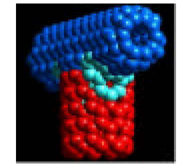
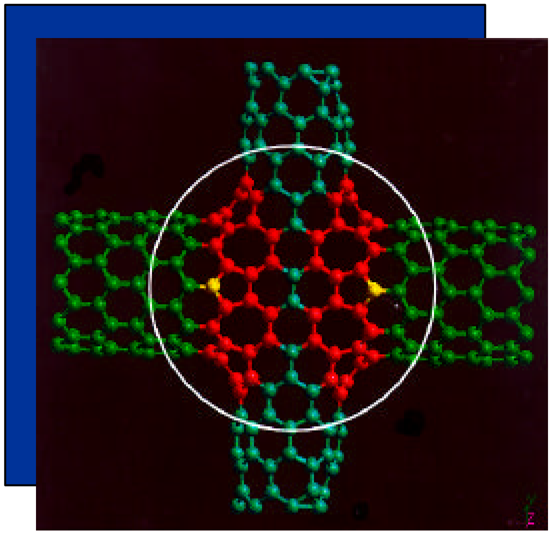
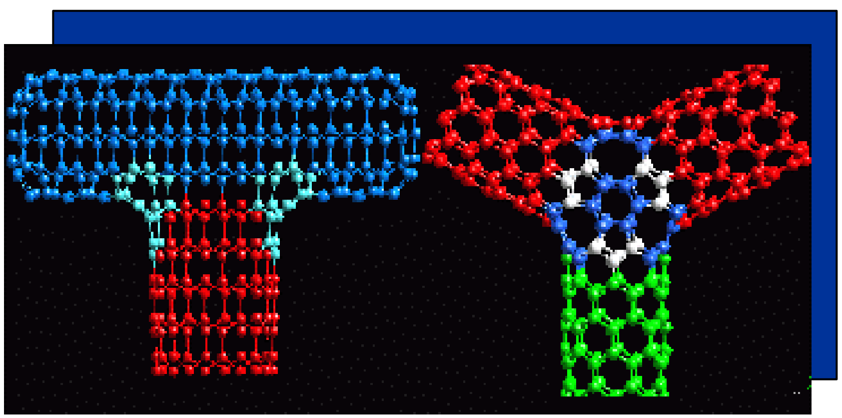
Computational Nanotechnology



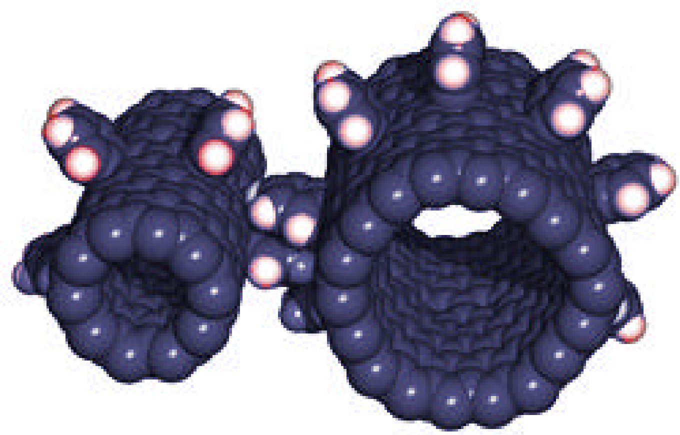


CNT Molecular Network

- Large scale computer simulations based on ab initio methods enable understanding nanotube characteristics and serve as design tool
  - Evaluation of mechanical properties
  - Evaluation of electronic properties
  - Electron transport in CNT devices
  - Functionalization of the nanotubes
  - Design of electrical and mechanical devices
  - Evaluation of storage potential (H_2, Li)



CNT “T” and “Y” Junctions



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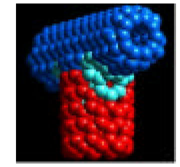
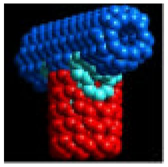
Carbon Nanotube Applications



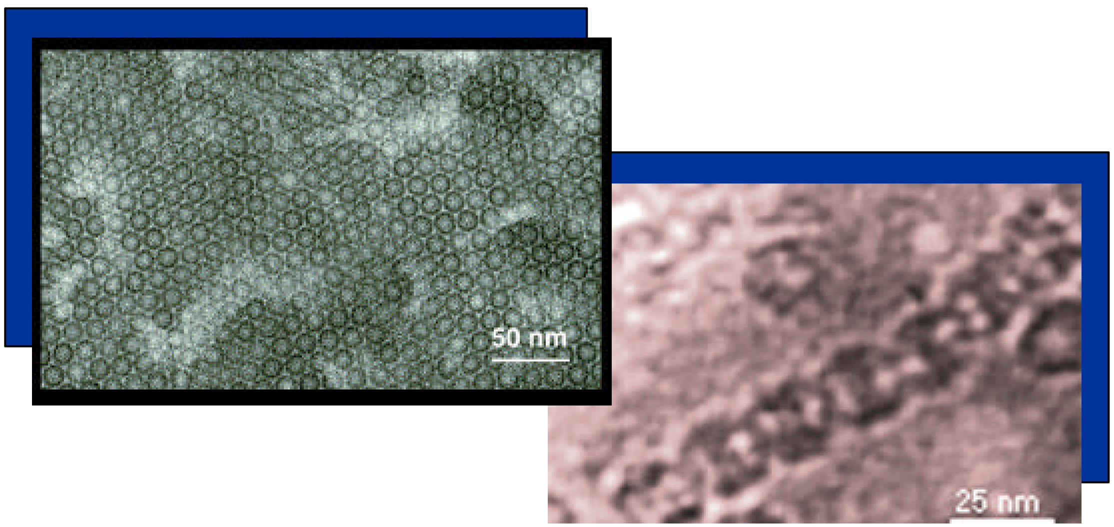
- Quantum wire as interconnects
- Carbon nanotube based molecular electronics, computer systems
- AFM based imaging, nanomanipulation
- Nanotube sensors: force, pressure, chemical…
- Nanotube biosensors, bionic eye, bionic ear
- Molecular motors, Nanoelectromechanical Systems (NEMS)
- Hydrogen storage, lithium storage
- Field emitters for instrumentation
- Flat panel displays
- High strength, light weight composites, cables
- Multifunctional materials

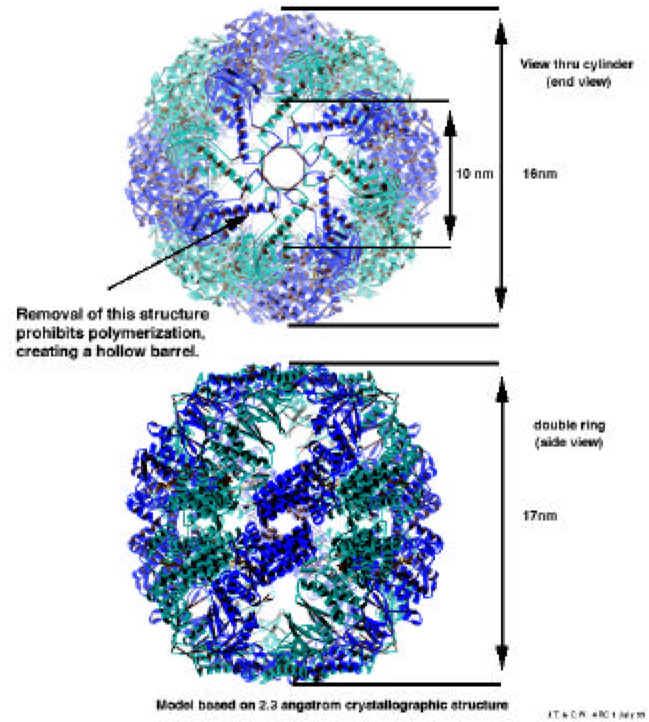
Protein Nanotubes



- Heat shock protein (HSP 60) in organisms living at high temperatures ("extremophiles") is of interest in astrobiology

- HSP 60 can be purified from cells as a double-ring structure consisting of 16-18 subunits. The double rings can be induced to self-assemble into nanotubes.





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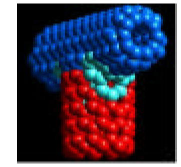
Summary



- A scientific and technical revolution has just begun based upon the ability to systematically organize and manipulate matter at nanoscale. Payoff is anticipated in the next 10-15 years.

- A National Nanotechnology Initiative (NNI) is in place and expected to bring together academia, industry, funding agencies, government laboratories and professional societies in pushing the frontiers of nanotechnology.

EXCITING TIMES ARE AHEAD OF US!